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GOODYEAR AIRCRAFT CORPORATION

AKRON OHIO

A STUDY OF AIRSHIP ROTARY DERIVATIVES

BuWeps Contract NOw 60-0229c

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LIST OF SYMBOLS

L	-	Envelope or Hull Length, Ft.
D	-	Maximum Diameter of Hull, Ft.
L/D	-	Hull Fineness Ratio
R	-	Airship Turning Radius, Ft.
R/L	-	Turning Parameter
D.C.	-	Dynamic Center of Hull
C.B.	-	Center of Buoyancy of Hull
VOL = $\forall$	-	Volume of Hull, Ft^3
S_T	-	Total Tail Area (Exposed Tail Area + Hull Area Included between Opposite Fins), Ft^2
l_{t_δ}	-	Airship Tail Moment Arm, Distance between C.B. (or D.C.) and Flap Hinge Line, Ft.
V	-	Freestream Velocity Ft/Sec
ρ	-	Mass Density of Air Lb Sec^2/Ft^4
q	-	Dynamic Pressure, $\rho/2\ V^2$, Lbs/Ft^2
q	-	Pitching Velocity, Rad/Sec
r	-	Yawing Velocity, Rad/Sec
ω	-	Angular Velocity, Rad/Sec
α	-	Angle of Attack, Deg. or Radians
α_{CB}	-	Angle of Attack at C.B., Deg. or Rad.
ψ	-	Yaw Angle, Deg. or Radians
$\dot{\alpha}$	-	Rate of Change of Angle of Attack, Rad/Sec
$\ddot{\alpha}$	-	Angular Acceleration, Rad/Sec^2
Γ	-	Tail Dihedral Angle, Deg. or Rad.
q'	-	Non-Dimensional Angular Velocity, $\frac{ql}{V}$
$\frac{\partial L}{\partial \omega}$	-	Lift Due to Pitching Velocity, Lbs/Rad/Sec
C_{L_q}	-	Rotary Lift or Lift Damping Derivative, Per Rad.
C_{L_ω}	-	Rotary Lift or Sideforce Derivative, Per Rad.
C'_{L_ω}	-	$C_{L_\omega}\left(\frac{\forall^{1/3}}{V}\right)$ Per Rad/Sec
$(C_{L_\alpha})_t$	-	Lift-Slope of Isolated Tail, Per Rad
C_{m_q}	-	Rotary Pitching Moment or Damping Moment in Pitch Derivative, Per Rad.
C_{m_ω}	-	Rotary Pitching or Yawing Moment Derivative, Per Rad

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LIST OF SYMBOLS - continued

C'_{m_ω} = $C_{m_\omega}\left(\frac{V^{1/3}}{V}\right)$ Per Rad/Sec

C_{Y_r} = Rotary Sideforce or Sideforce Damping Moment, Per Rad.

C_{n_r} = Rotary Yawing Moment or Damping Moment in Yaw Derivative, Per Rad

η_F = Hull-Tail Force Interference Factor

η_M = Hull-Tail Moment Interference Factor

d_1 = Tail Force Damping Correlating Factor

d_2 = Tail Moment Damping Correlating Factor

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A STUDY OF AIRSHIP ROTARY DERIVATIVES

I. SUMMARY

The predictability of airship stability and flying characteristics is highly dependent upon the contribution of the rotary lift, sideforce, pitching moment, and yawing moment derivatives. These derivatives, also referred to as the damping coefficients, are due to the pitching or yawing velocity of the airship. Since recent tests on a non-rigid airship (references 1 and 2) indicated some discrepancy between these measured values and those values used in present airship analyses, a limited technical review and analysis of available data on rotary derivatives for airships has been performed and a modified method for determining such derivatives for use in predicting the stability and flying characteristics of airships is presented. This study has been performed under Bureau of Naval Weapons Contract NOw 60-0229c.

The only modern tests performed to obtain airship rotary derivatives are reported in References 1 and 2 and were conducted in 1953-1954. All other tests of such a nature were conducted in the approximate period between 1915 and 1935. There were four experimental methods utilized to obtain the rotary derivatives for airships in the past and they are:

(1) the aerodynamic oscillator in a wind tunnel
(2) curved or bowed models in a wind tunnel
(3) models rotated on a whirling arm in a curved channel
(4) full-scale turning trials of airships

The majority of test data concerning rotary derivatives were obtained with the aerodynamic oscillator and primarily by British tests on models of rigid airships prior to 1930. There are four tests utilizing curved models for which data are available and only two tests, other than the recent tests of References 1 and 2, which utilized the whirling arm technique. Since the derivation of rotary effects by utilization of full-scale airship turning trials is mainly a correlating process and not an experimental measurement of any rotary derivative itself it is not considered of prime importance in this study.

In general the correlation and comparison of all the available test data is not considered as good as it could be. The data is very limited in its scope as to the effects of various parameters (such as hull fineness ratio, tail size, and tail moment arm) on the rotary derivatives. In addition much of the data for similar parameters show considerable scatter which may be due to experimental errors or interpretation of the data. During this study it became apparent that all

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of the various test methods have their limitations but that the curved model or whirling arm tests yield the most reliable and consistent results and data obtained from these tests are more favored than the aerodynamic oscillator experiments. Since approximately 70 percent of the data is of this latter type, which only provides direct measurement of the damping moment and not damping forces, it immediately is evident that insufficient reliable data of much significance in the scope of the various parameters is available for presenting a completely justifiable and final method for predicting the rotary derivatives for airships.

However, within the time allotted by the present contract an analysis of the available data has been performed and a means of predicting the rotary derivatives has been evolved for small disturbances or for maneuvers which do not exceed angles of attack and angular velocities beyond which the rotary derivatives are non-linear. The method presented is based on the assumption that the contribution of the hull and tail to the rotary effects can be individually added and that the effects of the car and other appendages are small or negligible. The prediction of the derivatives is a mixture of theoretical and empirical considerations and available test data.

The significant rotary derivative data are presented in Figures 5, 6, and 7, of this report. A comparison is made in the report of the differences in the rotary lift and pitching moment as predicted by the method presented in this report and as estimated in Reference 22 for the ZPG-3W airship. There are significant differences in the rotary lift and especially the moment. The evaluations point out the need for further effort to be expended to analyze and correlate existing data and the requirement for more systematic experimental data in order to establish trends in the derivatives due to the many variable parameters. A brief discussion of the type of tests required is given in Section VII of this report.

The method presented in this report is believed to be more rigorous than that previously utilized for modern non-rigid airships but with additional effort and/or acquisition of more data the accuracy could be much enhanced.

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II. INTRODUCTION

As a result of any incidental disturbance, an airship will always experience a course deviation involving each degree of freedom in the plane of the disturbance. In any plane, the airship is free to translate both axially and transversely and to rotate about a normal axis. The attack angle set up by the initial disturbance produces a moment which initiates an angular velocity, which increases the attack angle farther and which is resisted only by a damping moment due to rotation. In addition, a transverse force due to the attack angle which is augmented by a damping force due to rotation causes a transverse velocity which reduces the attack angle. Also the resulting drag increase due to both the attack angle and the rotation reduces the airspeed. If the airship is dynamically stable, the overall effect of these motions is that the attack angle is reduced to zero and the airship takes a new course whose direction makes an angle with the original course. Rectilinear dynamic stability is defined as the quality of the airship which causes the angular velocity and attitude resulting from an initial disturbance of the motion of the airship to decrease with time without benefit of control adjustment and with relatively small consequent course deviation. Curvilinear dynamic lateral stability of an airship is defined as the quality which causes the flight path resulting from an initial disturbance to approach asymptotically a circle of definite radius. Only rectilinear dynamic stability is considered in this report since the curvilinear radius approached asymptotically can be infinite and it thus follows that rectilinear dynamic stability always implies curvilinear dynamic stability as well, although the degree or amount of stability in each case might be different. The various combinations of airship rectilinear and curvilinear stability and instability are illustrated graphically in Figure 1. Evaluation of the criteria for dynamic stability, therefore, involves a study of the nature and origin of the damping forces and moments which play such a large part in determining the flying qualities of an airship.

Being statically unstable, the airship cannot (without being steered) maintain its original heading. Instead, when disturbed, it will take a curvilinear path in the plane of the disturbance. In fact, all airship motion is to some degree curvilinear. Furthermore, the dynamics of motion is the simplest possible when the curvilinear motion is steady; i.e., circular flight. Consequently, a study of dynamics of airship motion may be conveniently reduced to a study of the forces and moments and the motions experienced in curvilinear flight. A clear physical picture of the damping forces and moments can be gained by considering their origin. An airship flying on a straight course with an attack angle (straight-pitched flight) will experience the same attack angle at every point along the length of the airship in the same reference plane. An airship flying with a velocity (V) in a circular path of radius (R), however, has an angular velocity ($\omega = \frac{V}{R}$).

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From the nature of the motion, it is obvious that the airship experiences a continuous change in the effective attack angle along its length. The direction of motion at any point on the airship a distance (x) aft of dynamic center (D.C.) makes an angle ($\tan^{-1}\frac{\omega x}{V}$) with the direction of motion at the D.C. In other words, points on the airship aft of the D.C. experience larger attack angles while points forward of the D.C. experience smaller attack angles than those experienced at the D.C. Thus, the damping forces and moments may be defined respectively as the differences between the forces and moments acting on the airship when on a curved course and the forces and moments acting on the airship when on a straight course with the attack angle at the D.C. being the same in both cases. The ratio of the forces (F) and the moments (M) due to a small angular velocity (ω) to the value of (ω) which produces them are called the rotary derivatives; i.e., $F_\omega = \left(\frac{\partial F}{\partial \omega}\right)_\alpha = \left(\frac{F}{\omega}\right)_\alpha$ and $M_\omega = \left(\frac{\partial M}{\partial \omega}\right)_\alpha = \left(\frac{M}{\omega}\right)_\alpha$.

However, it is more convenient to express these rotary derivatives in terms of non-dimensional coefficients of the type (C_{F_ω} and C_{M_ω}).

That is;

$$F_\omega = C_{F_\omega} \rho/2 \; V \; \mathcal{V} = \left(C_{F_\omega} \frac{\mathcal{V}^{1/3}}{V}\right) q \; \mathcal{V}^{2/3}$$

and

$$M_\omega = C_{M_\omega} \rho/2 \; V \; \mathcal{V}^{4/3} = \left(C_{M_\omega} \frac{\mathcal{V}^{1/3}}{V}\right) q \; \mathcal{V}$$

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III. ANALYTICAL AND EXPERIMENTAL METHODS OF ROTARY DERIVATIVE EVALUATION

A. ANALYTICAL

Accurate appraisal and evaluation of airship flying qualities is dependent on the ability to predict the magnitude of rotary derivatives. The investigation of this problem has been undertaken by various analytic and experimental means. Present day analytic estimates of the forces and moments resulting from rotary motion of an airship are based upon the assumption that the rotary effects can be predicted by summing up the contribution of each airship component. Early investigators at first thought that the analysis of simple potential inviscid flow might yield the basis for the determination of the contribution of the hull to the rotary derivatives by analytically determining the zonal pressure distributions in combined flows as presented in reference 3. However, on integrating these zonal pressure forces over the length of a hull or body of revolution the resultant lateral force and moment are zero. Consequently, the results of these theoretical analytic procedures are useful only when examining the aerodynamic pressures in curvelinear flight which though not the purpose of this report do represent one of the most stringent conditions which should be contemplated when estimating the stresses to be carried by the airship hull or envelope.

The major effect of rotation is to cause an increase in the attack angle experienced by the tail which is theoretically equal to $(\frac{l_t \omega}{V})$. Then, using the pertinent static aerodynamic characteristics of the empennage the incremental lift which produces a change in the total lift and/or pitching moment may be calculated. The effects of downwash on the empennage produced by the generation of circulation along the hull is generally neglected as are the effects of the car, the outriggers, the propellers and other protuberances.

The preceding discussion indicates that the hull contribution to the rotary lift and moment are not readily solvable by analytical means and test data, which does show a hull contribution, must be relied upon. The rotary contribution of the tail does appear to be calculable.

B. EXPERIMENTAL METHODS

Several experimental techniques have been devised and used to measure the rotary derivatives for vehicles or bodies moving in a fluid medium. The measurement of airship rotary derivatives have been performed in the past by three methods, the whirling arm, the aerodynamic oscillator, and by curved or bowed models.

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In addition, these derivatives have been deduced, but not directly measured, by observations and data taken during full-scale turning trials of some airships. Since this latter method is not a direct measurement of the rotary effects and is highly dependent upon simplified equations of motion and other measured parameters it is not utilized in this study except for two or three examples for which data were readily available.

Each method utilized to determine airship rotary effects has its limitations and possible inaccuracies. A complete evaluation of the theory and application of each experimental method is beyond the scope of this study and therefore only a brief description and resume of the various methods is presented in this report.

1. The Whirling Arm

Some of the earliest attempts to measure the rotary forces and moments of an airship were made by the Italians on a device known as a whirling arm in which a scale model is mounted on the end of a radial arm which is forced to turn in a circular orbit of known radius. The theory of the whirling arm is relatively simple. In early experiments the forces and moments were first measured (either by direct measurement or integration of pressures) with the model mounted on the whirling arm of known radius and rotated in steady circular motion and secondly the same model, if possible, was tested in a conventional wind tunnel with the attack angle at the D.C. being equal in both cases. The differences between the two measurements of the forces and moments are then representative of the rotary effects of the configuration and can be expressed by the previously defined non-dimensional coefficients. However, particular care must be exercised when determining the differences between the two measurements in order that local variations in the angle of attack and velocity are accounted for in the analysis. In the whirling arm experiments reported in References 1 and 2 a different approach was utilized based on more modern techniques. The whirling arm was employed to obtain both the static and rotary effects of the airship configurations. This concept consists of testing the model mounted at various radial distances from the center of the whirling arm which essentially is representative of maneuvering flight for a range of turning radii and angular velocities. Data obtained in this manner was linearly interpolated to zero turning radius or angular velocity for determination of the static derivatives, and the rotary lift and moment slope at or near zero angular velocity could be obtained by plotting the data against the non-dimensionalized angular velocity. This method which eliminates the need for

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determining the static derivatives from tests in a conventional wind tunnel which could result in differences due to turbulence, Reynolds number, tare corrections and other such effects appears to be more reliable than the early tests which were usually conducted with one model location on the radial arm (i.e. one value of turning radius and angular velocity).

However, the whirling arm technique for obtaining rotary (or static derivatives) is subject to inaccuracies inherent in the system, as in any system, which may or may not be corrected for in the data obtained. One of the major difficulties in the whirling arm technique is the fact that the model is rotated thru its own wake and the velocity and flow over the model is distorted until the patterns are quite uncertain and are not representative of free-stream circular flight. This together with the difficulties in correcting for the centrifugal effects on the model, its balance system and instrumentation introduces errors which may be quite large when compared with the quantities being measured.

2. The Aerodynamic Oscillator

The principle of the aerodynamic oscillator is well known and used extensively in the experimental determination of airplane rotary or damping effects. In this system a model is allowed to oscillate about an axis thru its center of mass by a device which supports the model at a given attitude in a conventional wind tunnel and allows only one degree of freedom with a motion which is elastically restoring. With the model artificially deflected and left to oscillate with the tunnel on, the rate of decay of the angular amplitude is measured. The theory underlying the evaluation of the experiment assumes that the aerodynamic moment has one component which is proportional to the attack angle (α) and the square of the speed (v), whereas the other is proportional to the product of the angular velocity of rotation (ω) and the speed itself; while the whole must equal the moment of inertia (I) times the angular acceleration ($\ddot{\alpha}$) and the friction damping moment (M_F) of the apparatus. In terms of non-dimensional coefficients, this can be expressed as:

$$\left[\frac{\mathcal{V}^{1/3}}{V}\left(C_{M_\omega}\,\omega + C_{M_\alpha}\,\alpha\right)\right] q\,\mathcal{V} = I\,\ddot{\alpha} + \left(\frac{\partial M_F}{\partial \omega}\right)\omega$$

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Then, by observing the logarithmic decrement μ, we may solve for $C_{M_{\dot\omega}}$ by the expression

$$C_{M_{\dot\omega}} = \frac{2\mu I - M_F}{\left(\frac{\mathcal{V}^{1/3}}{V}\right) q \mathcal{V}}$$

M_F may be determined by a repeat experiment wherein the model is oscillated with zero wind tunnel velocity. In addition the rotary effects of the apparatus usually must be determined and subtracted as a tare value by oscillating the apparatus alone at the same tunnel velocities. As the model is restrained to one degree of freedom the rotary force coefficients (C_{Y_ω} and C_{X_ω}) can not be measured and this constitutes a major shortcoming of the method. There are basic aerodynamic errors associated with the oscillation method of determing the rotary moment coefficients. The first stems from the definition of a rotary moment as the moment due to rate of rotation (ω) with the attack angle (α) remaining constant. In the oscillation experiments however, (α) does not remain constant. In fact $\frac{d\alpha}{dt} = \omega$.

Consequently the rotary moment coefficient is proportional to the logarithmic decrement only so long as it does not depend on the attack angle. A Second error arises from the cyclic variation of the angular accrleration. These variations intreduce accelerations in the airstream which has the effect of a variable additional moment of inertia. As a result of these errors, the oscillation method can yield satisfactory rotary derivative values only when the model oscillates slowly and with small amplitudes about the zero attack angle. Other possible sources of error stem from a possible time lag in the tail contribution, and as noted in recent airplane tests the possibility (as noted above) of variations in the magnitudes of the rotary effects with the frequency of the oscillation. It is also to be understood that this rotary moment determined from the oscillator includes the effects of $C_{M_{\dot\alpha}}$ which accounts for time-lag effect of pressure due to sudden attack angle changes which in the case of a bare hull may be small or negligible but the tail contribution to $C_{M_{\dot\alpha}}$ is the prevously noted time lag in tail contribution or downwash lag and might be significant. In the present analysis no attempt is made to separate C_{M_ω} and $C_{M_{\dot\alpha}}$ and it is assumed that the effects of $C_{M_{\dot\alpha}}$ are negligible or that they are included in the total derivative.

3. Curved or Bowed Model Techniques

The measurement of aerodynamic parameters in curvilinear flight by the method of curved or bowed models in a conventional wind tunnel was independently derived by several people during the late 1920's and

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early 1930's. Reference 4 presents some of the data obtained in Germany from an experiment on a 1/75-scale curved model of the LZ-126 airship (U.SS. Los Angeles). References 5 and 6 derive the theory of curved models and present the results of an experiment conducted on 1/64.64-scale models of the non-rigid V-2 airship. Another derivation of the bowed model theory is given in Reference 7 along with data obtained on two curved models of the "Shenandoah" rigid airship.

The derivation of the theory and equations for bowed models is adequately reported in the above references and will not be repeated in this report. In resume, however, the following discussion is presented. The elemental or zonal forces experienced by an airship in curvilinear flight are dependent on the local attack angles, the local surface areas, and the local velocities. The continuous change in the local attack angles and velocities experienced along the length of an airship in curved flight may be simulated by the use of a curved or "bowed" model held in a straight airstream. The two conditions which define the equation of the bowed axis are the conformal transformation of all the local attack angles and the conservation of all the local axial lengths.

As derived in References 5 and 7 the resultant equation for the bowed axis of an airship represents a hyperbolic curve. However, Reference 8 reports the test results of a model airship constructed with a circular arc as the axis and Reference 9 states that the difference in the model ordinates involved would have been smaller than the tolerances which would be obtainable during manufacture. The use of a circular arc model would allow possible savings in construction costs and time.

In order to obtain accurate similitude between the curved model tests and actual curvilinear flight the local velocity variations must be duplicated. The local velocities experienced by an airship in circular turning are proportional to the path radius of the surface element. The stern, of course, swings on a larger radius than the bow and is thus exposed to higher velocities. Consequently, a suitable linear velocity gradient should be imposed across the tunnel although some investigations indicate only small differences in some of the rotary effects with and without velocity gradients. Now, similar to the whirling arm experiment the forces and moments measured on the bowed model must be subtracted from the forces and moments on a straight

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model with the same attack angle at the dynamic center to obtain the rotary forces and moments from which the non-dimensional coefficients may be calculated.

However, the analogy between the curved model and circular flight is somewhat strained in some respects. On the model, the lengths of the surfaces are slightly different on the two sides and consequently the local velocities will have slightly different magnitudes. Furthermore, in curved flight, the air in the boundary layer is subjected to centrifugal forces not imposed on the curved model. The errors introduced by these dissimilarities, however, have been proven by experiment to be small and therefore probably negligible.

Another source of possible error or discrepancies which might be mentioned is the effect of the netting or screens, used to obtain the desired velocity gradient, on the turbulence of the flow. This, however, is probably small and the values can probably be adjusted for this discrepancy. Some investigators have objected to the curved model experiments on the basis that a separate curved model must be built for each turning radius or angular velocity to be investigated. However, both Gourjienko (Reference 6) and Smith (Reference 7) have stated that their calculations and tests have proven that this is not necessary and that one curved model is sufficient. However, since some doubt still exists as to the validity of some assumptions used in the Reference 6 arguments and since the Reference 7 conclusion is based on only two models of different curvature the writer feels that within the scope of this study a definite conclusion cannot be reached on the use of one curved model to obtain the complete range of the rotary derivatives for all variables involved, although it appears very possible.

4. Comparative Reliability and Accuracy of the Various Experimental Methods

This is not a discussion and comparison of actual data but only a brief dissertation of the methods which appear to be most promising for the accurate determination of rotary derivatives. The many errors and corrections which are inherent or must be made to damping data obtained by the aerodynamic oscillator along with its inability to directly measure the rotary forces indicates the need for a better method as far as airship dynamics are concerned. It is possible that with modern equipment and advanced techniques this method might yield values of the rotary moment within acceptable accuracies although the

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test of an airship model on present oscillators would require model sizes resulting in very low aerodynamic loads which would further reduce the probable accuracies.

The whirling arm technique as utilized in References 1 and 2 appears to be much better than older whirling arm tests and much more useful and accurate than the aerodynamic oscillator. However, the inherent difficulties introduced by rotating the model in its own wake, although not insurmountable still remains a major problem. Reference 2 states that this effect is minimized due to the test velocity utilized although no proof is presented that the minimized effects are negligible. The centrifugal corrections required for whirling arm tests, especially where pressure measurements are desired, also offer difficulties in data reduction or interpretation not found in the other types of experimental methods.

The technique of the bowed or curved model to obtain airship rotary effects appears to be the most promising with regard to the reliability and accuracy of the data. The model (or models) can be tested in conventional wind tunnels without new or specialized equipment or devices being required. Corrections to the data due to test conditions are essentially the same as used in all wind tunnel tests, for which an extremely large amount of data is now available. The only extra item that might be considered is the effect of the curvature on any tunnel wall corrections since at angles of attack one end of the model would be much closer to the tunnel wall than the other end. If a series of tests or further studies can fully support the contentions that one curved model can be employed to investigate the variation of the rotary derivatives with all its variable parameters the major objection to the bowed model technique, namely the cost and time involved in constructing and testing models of varying curvature, would be removed. It is true, of course, that even if only one curved model is necessary it will cost slightly more to design and build compared to a straight model which in addition, should be built and tested at the same time. As in all types of airship model testing, and especially the bowed model technique, the accuracy of the data is often dependent upon the differences between small measured numbers, so in the testing of a curved and straight model built to the same scale and tested in the same tunnel it is probably important to reduce all extraneous effects of different tunnels, mounting equipment, and model scales.

In conclusion, it appears that either the modern whirling arm technique employed in References 1 and 2 or the method of curved models utilized and reported in References 5, 6, 7 and 8 offer the best method for experimentally determining the airship rotary derivatives.

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IV DATA ANALYSIS AND REVIEW

A. INTRODUCTION

The three methods which have been used to experimentally determine the rotary derivatives of an airship are the aerodynamic oscillator, the whirling arm, and curved or bowed models. The majority of available published data has been obtained by tests with the aerodynamic oscillator with a very limited amount of data available from whirling arm and curved model tests. Unfortunately, practically all model measurements of airship rotary derivatives were conducted during the period between 1920 and 1935 without the benefit of modern techniques and equipment to improve the data accuracy and standards of nomenclature and methods. It is also noted that all of the available airship rotary test data (except one test) obtained by the oscillation technique were derived from British Reports and Memorandums published in the period between 1918 and 1926 and were almost exclusively for rigid airships with fineness ratios between six and ten. During this period many of the investigators utilized varying methods of presenting their observed or derived values for the damping moment coefficient with often little or no concise explanation of the varying terminology and dimensions involved. In addition, many of the investigations performed with all three techniques consisted of tests of complete models with the consequent loss of direct measurement of individual hull and tail contributions.

Although a search for rotary derivative information for airships resulted in numerous reports and data which were available to the contractor, the large variance in the magnitude of the reported or derived rotary derivatives indicated the need for a more thorough evaluation of these values. About ten (10) years ago Goodyear Aircraft personnel initiated a preliminary correlation of available airship rotary derivative information and some data have been gleaned from these efforts. However, since only one or two plots of these data or correlating parameters are available without detailed calculations or explanations of the method and values used this data is only utilized when absolutely necessary.

Therefore, since much of the available data showed much scatter and some doubt existed as to its applicability, a complete reevaluation of the data given in the various reports, including

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References 1 and 2, was initiated. One of the basic reasons for this re-evaluation was the form in which many of the rotary derivatives have been expressed. For example, the rotary lift slope has been expressed as a numerical value over the velocity (i.e. $C_{L_q} = 100/V$) with a dimensional value of the slope per rad/sec. This is not a non-dimensional form and is not consistent with present aerodynamic practice and nomenclature. In all recent airship stability analyses this form has been non-dimensionalized by multiplying the value by $(V/\forall^{1/3})$ of the full-scale airship being analyzed. That this relationship is apparently correct can be shown as follows. The lift of an airship due to its pitching velocity (rotary lift) can be expressed in familiar and normal airship notation consistent with standard engineering practices as:

$$\frac{\partial L}{\partial \omega}\,\omega = C_{L_\omega}\,\rho/2\;V\,(Vol)\,\omega$$

where:

$\frac{\partial L}{\partial \omega}$ = lift due to pitching velocity, $\frac{\text{lbs sec}}{\text{rad}}$

ω = pitching velocity, rad/sec

C_{L_ω} = rotary lift slope, per radian

ρ = density of air, lb sec^2/ft^4

V = free stream velocity, ft/sec

$Vol = \forall$ = volume of hull or envelope, ft^3

Note: Generally the pitching velocity is given by q, but since the dynamic pressure (also denoted by q) is introduced later, ω is substituted at this time.

Since the standard method of non-dimensionalizing airship static aerodynamic lift is by the volume to the two-thirds power and the dynamic pressure it is apparent that the following equality exists for the above equation.

$$C_{L_\omega}\ \rho/2\ V\,(\mathcal{V})\,\omega = C_{L_\omega}\ \rho/2\ V^2\left(\frac{1}{V}\right)\mathcal{V}^{2/3}\,(\mathcal{V}^{1/3})\,\omega$$

Therefore:

$$\left(\frac{\partial L}{\partial \omega}\right)\omega = \left[C_{L_\omega}\left(\frac{\mathcal{V}^{1/3}}{V}\right)\right] q\,\mathcal{V}^{2/3}\,\omega$$

$$\left(\frac{\partial L}{\partial \omega}\right)\omega = C'_{L_\omega}\ q\,\mathcal{V}^{2/3}\,\omega$$

where:

$$C'_{L_\omega} = C_{L_\omega}\left(\frac{\mathcal{V}^{1/3}}{V}\right)$$

and has dimensional units of per radian/sec.

Therefore:

$$C_{L_\omega} = C'_{L_\omega}\left(\frac{V}{\mathcal{V}^{1/3}}\right) = C_{L_q}$$

Similarly the rotary moment can be expressed as:

$$\left(\frac{\partial M}{\partial \omega}\right)\omega = C_{M_\omega}\ \rho/2\ V\,(\mathcal{V}^{4/3})\,\omega = \left[C_{M_\omega}\left(\frac{\mathcal{V}^{1/3}}{V}\right)\right] q\,\mathcal{V}\,\omega$$

and $$C_{M_\omega} = C'_{M_\omega}\left(\frac{V}{\mathcal{V}^{1/3}}\right) = C_{M_q}$$

Identical relations also exist for the rotary sideforce coefficient (C_{Y_r}) and yawing moment (C_{n_r}). These then have been the generally accepted means of converting the rotary derivatives expressed as a numerical value over V into a non-dimensional rotary derivative.

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However, some of the analyses made for this report indicate that if the model rotary data is expressed as a number divided by V it is not directly applicable to other full-scale airships unless it is first converted to the completely non-dimensional form by use of the original model $V^{1/3}$ or barring this by some other model scale factor which might be determined. Therefore in the present analysis all rotary derivatives are presented in, or have been converted to, the completely non-dimensional-slope form from original data whenever sufficient data from the particular report were readily available.

After considerable effort had been expended in the attempt to re-evaluate all the old reported data it became evident that the magnitude of the task (due in part to the lack of readily available dimensional data) could not be accomplished within the scope of the present contractural study. However sufficient data has been obtained to show some trends and to determine some correlating parameters.

The majority of the rotary derivatives obtained by the aerodynamic oscillator method are obtained from data presented in Reference 10 through 17. The results of whirling arm experiments are derived from data given in References 1, 2, 18 and 19. The test data of curved or bowed models is given in References 4, 6, 7, 8 and 9.

B. DISCUSSION AND PRESENTATION OF DATA

1. Hull Rotary Effects

a. Lift Due to Pitching or Yawing Velocity

The effect of hull fineness ratio on the rotary lift and moment due to the hull alone is given in Figure 5 and includes all airship data which is available for the bare hull configuration. It should be noted that bare hull (or hull alone) data in the case of rigid airships often refers to the hull with the keel car attached. However, although this alters the hull shape somewhat it is felt that the effect would probably be small and negligible. It can be seen from Figure 5 that insufficient data exists for the hull rotary lift or side-force to completely define its most probable value and variation with fineness ratio. This is due to the fact that the oscillation technique (which amounts to approximately 70% of all our available data) only yields the rotary moment effect. In recent airship estimates it has generally been assumed that the rotary lift and side force slopes are negligible or included in other estimates of lift slope. It is evident however that the value should be estimated to have a value of about .15/rad to .20/rad for L/D ratios between 4 and 6 and might be represented by the line shown in Figure 5. It appears feasible that the rotary lift or side force might have a definite variation or increase with fineness ratio. The rotary lift coefficient for the curved model of the V-2 non-rigid airship (Ref. 6) is much higher and does not appear consistent with the other data, meager though it may be. This data point was evaluated from data obtained with the model at approximately 9° angle of attack of the C.B., which corresponded to the attack angle at the C.B. for which the model was bowed. This is the proper angle at which to evaluate the data since then the nose would be at zero angle of attack as is usually regarded in curvilinear motion with increasing attack angle as one would move aft towards the tail. However, evaluation of the data at $\alpha_{CB} = 0°$ yields a C_{L_Q} value of approximately .16 which is more in line with other plotted data in Figure 5. This again reverts to the old controversy as to what attack angle should be used when evaluating curved model and whirling arm tests, or is the data valid for all attack angles. This question could not be resolved within the scope of the present analysis and therefore the value determined at

α_{CB} = 0° is also shown in Figure 5. Until additional test data becomes available it appears that the faired line in Figure 5 represents the best value to use for the lift or sideforce due to pitching or yawing velocity.

b. Moment Due to Pitching or Yawing Velocity

The rotary moment data of Figure 5 shows considerable scatter and differences for hulls of approximately the same fineness ratio and even the same hull tested in both pitch and yaw. Particular attention is brought to the difference in C_{m_q} and C_{n_r} for the R-23 airship hull (Ref. 10). The value of C_{n_r} is almost 3 times the value of C_{m_q} and this is believed due to the large triangular keel which was part of the bare hull model. Attention is also directed to the data obtained from the recent whirling arm tests performed at Stevens Institute of Technology and reported in References 1 and 2. In the first place the value of C_{m_q} hull is given in Reference 1 as a positive value which is contrary to all other airship hull data. Therefore the sign only was arbitrarily changed to negative although it is recognized that the error (if any) in sign may have originated where it would also change the numerical value. This is supported somewhat by the C_{n_r} value which is negative and numerically much lower but which appears too low based on other data. Another disputed point is that shown for the whirling arm tests on a model of the "Akron" airship (Reference 19). This value was determined at ψ = 0°. The C_{n_r} at $\psi \cong$ 10°, which is the angle of attack corresponding to the whirling arm radius used, is approximately -.14 and shows better agreement with other data.

In an attempt to obtain some modern rotary derivative information from airplanes, a report of tests conducted in the curved wind tunnel at NASA Langley Field, Virginia in 1952 was obtained (Reference 20). In this investigation the effect of various fuselages, tail sizes and tail location on the damping moment were determined for a family of airplane configurations. The fuselages were bodies of revolution having circular-arc profiles and fineness ratios of 5, 6.67, and 10. However this fuselage data which would have been very useful due to the L/D's investigated does not agree with our airship data except at L/D = 10. This is no doubt due to the difference in shape (circular arcs V.S. ellipsoids) and cannot be utilized although two data points for L/D = 10 are given in Figure 5.

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One is the measured value of $\left[C_{m_q}\right]_{fuselage}$ at $\alpha = 0$ and the other value is derived from the difference between the complete model value and the faired value of the horizontal tail contribution.

Again, the scarcity of substantiating data over the full range of hull fineness ratios makes it extremely difficult to determine the most probable values of C_{m_q} or C_{n_r} of the hull. As might be expected the value of the rotary moment coefficients appear to increase with increasing L/D although there seems to be an abrupt upsurge at L/D = 9 or 10. From the data available it appears that the faired curve of rotary moment shown in Figure 5 is the best estimate that can be made for the airship hull contribution to the rotary derivative. However, it should be noted that the data is scattered and even a horizontal line of C_{m_q} (or C_{n_r}) = .22 from L/D = 4 to L/D = 9 might represent the variation of the hull rotary moment derivative.

2. Tail Contribution to Rotafy Effects

Generally it has been conceded in the past that the tail contribution to the airship rotary lift could be calculated with reasonable accuracy. However, after working with some of the data it became apparent that there was still much to be desired in the predictability of the tail rotary effects. Since the Reference 1 and 2 data had rotary lift and moment values for several types of tails the tail contributions (including the hull-tail interference) were determined from the measured data and compared with the calculated values derived from the following semi-theoretical equations:

$$\left[C_{L_q}\right]_{tail} = \frac{(C_{L_\alpha})_t \, S_T \, \ell_{t_\delta} \, \eta_F}{VOL}$$

$$\left[C_{m_q}\right]_{tail} = \frac{(C_{L_\alpha})_t \, S_T \, \ell_{t_\delta}^{\,2} \, \eta_M}{(VOL)^{4/3}}$$

where:

$(C_{L_\alpha})_t$ = isolated lift-slope of tail (Figure 2)

S_T = tail area (including hull area and effect of dihedral), Ft^2

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ℓ_{t_δ} = tail arm, C.G. to flap hinge line, Ft

η_F = hull-tail force interference factor (Figure 3)

η_M = hull-tail moment interference factor (Figure 4)

Similar equations were used for C_{Y_r} and C_{n_r} but it should be noted that some of the above parameters vary for the longitudinal (pitch) and lateral (yaw) cases. The above equations indicate that the rotary lift and moment are proportional to the geometric quantities

$$\frac{S_T \ \ell_{t_\delta}}{VOL} \quad \text{and} \quad \frac{S_T \ \ell_{t_\delta}^{\,2}}{VOL^{4/3}}, \text{ respectively.}$$

Therefore the measured slopes of Reference 1 and 2 are plotted in Figure 6 against these non-dimensional parameters. Also shown in this figure is the ratio of the measured slopes, evaluated from References 1 and 2, to the calculated slopes obtained from the above equations. These ratios are denoted as d_1 for the rotary lift (or sideforce) and d_2 for the rotary moment (pitching or yawing). The original intent was to include all of the available airship data on tail-contributions to rotary effects in such a plot but this is not possible within the scope or magnitude of this contract. The major reason is the lack of information in the old reports of the included hull area of the various models and even readily accessible data as to the tail-sizes and locations from which this might be estimated. This information can be obtained but not without the expenditure of considerable research and effort. For these reasons only the Reference 1 and 2 data are shown in Figure 6. Faired lines are drawn through the various parameters but it is unfortunate that these tests were not exactly conducted for evaluating such variations. If the tests had been conducted with a greater variation in tail size and for various hull-fineness ratios (variation of ℓ_{t_δ}) more exact variations of the tail rotary derivatives with the geometric parameters could be obtained. Some of the scatter in Figure 6 could probably be reduced and better correlation obtained between measured and calculated values by a re-evaluation of the hull-tail interference factors η_F and η_M, which is beyond the scope of this evaluation. The factors utilized in the calculated rotary effects were obtained from past correlations of measured and theoretical static derivatives, which

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do not include all of the recent non-rigid airship wind tunnel results. Spot checks of the applicability of these past correlations, which were based mainly on rigid airship data, indicate that the values of Figures 3 and 4 are too low and thus better correlation between measured and calculated rotary effects could be obtained. Some re-evaluation of the hull-tail interference factors has been done on Page 13 of Reference 21 but this data has not been compared with other recent data and has been used without proof of its agreement with other data and the variable parameters which exist.

However, since the Reference 1 and 2 data are not broad enough in the range of variables and only constitute a small portion of the total airship rotary derivative information it is felt that a correlation showing all the information would be better for the estimation of rotary effects. Therefore, the correlations of tail contributions initiated approximately 10 years ago by the contractor are shown in Figure 7, along with the current Reference 1 and 2 data. Figure 7 plots the tail damping factors, d_1 and d_2, as a function of the hull fineness ratio. The damping factors have previously been defined as the ratio of the measured rotary effect to the calculated or theoretical rotary effect. A significant item observed from this plot is the large difference in magnitudes of the force (d_1) and moment (d_2) factor as obtained from the old data and the relatively minor differences in these factors derived from the recent Reference 1 and 2 data. However, part of this discrepancy may exist due to the nature of the old evaluations which could not be directly checked since only the final resulting curve, not the calculations, are available and because the majority of the geometric variables are not readily available in the published reports and their determination could not be performed within the magnitude of this contract. Again it is emphasized that the tail damping factors should be plotted against the geometric ratios utilized in Figure 6 rather than the hull fineness ratio but as noted previously this was not possible at this time.

Evaluation of the Reference 1 and 2 data indicate that for all tail configurations the average difference between d_2 and d_1 from pitch data is negligible ($d_2/d_1 \cong 1.00$) and from yaw data is approximately 10% ($d_2/d_1 \cong 1.10$). This compares with an average d_2/d_1 ratio for the other old data of all types of 1.45. All of the plotted tail damping force factors agree fairly well and have a value of $d_1 \cong 1.30$.

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The tail damping moment factors plotted in Figure 7 do not show any consistent pattern or agreement. It is the writers opinion that much of the old rotary moment data obtained by the oscillation technique is of questionable value or correctness and that the large difference between d_2 and d_1 cannot be satisfactorily explained or justified at this time. Allowing some weight for this data it is estimated that the d_2 factor might be equal to 1.60. There might be some variation of these factors with fineness ratio but it cannot be ascertained from the present data, except as an educated guess or supposition. Until further effort is expended on these problems it appears that the best values that can be utilized from this analysis for estimating rotary derivatives for present day airships is that $d_1 = 1.30$ and $d_2 = 1.60$.

3. Comments and Observations

a. Other Contributions to Dynamic Forces and Moments

It has usually been assumed that the rotary effects of airship cars, radomes, antennas and other appurtentances have little or negligible effect on the rotary lift, sideforce, and moments. This has not always been substantiated by model tests and especially so in the recent whirling arm tests of Reference 1 and 2. These tests are quoted since the configurations tested are those utilized on modern non-rigid airships while practically all other data is for rigid airships with much different car or gondola configurations. These data show car contributions to the rotary lift which are opposite in sign (direction) to and almost 70% of the hull contribution. However, the car contribution to the rotary sideforce which might be expected to be appreciable although opposite in sign is only 20 to 30% of the hull contribution. The difference in car yaw and pitch effect, which is opposite to that anticipated is probably due to the difference in bare hull rotary lift and sideforce in which the rotary lift is approximately 30% or more greater than the rotary sideforce even though the body is completely symmetrical. It should also be noted that the rotary lift and side force contributions of a large car and a small car (both tested on the same hull) are about equal. The rotary moment contributions of the cars are too erratic to be accurately evaluated.

Another item tested and reported in References 1 and 2 was the effect of a large elliptical radome (ZPG-2 type) compared to a

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small cylindrical radome of the ZSG-4 and/or ZS2G-1 type. These radomes were attached to the bottom of the car and in pitch the measured difference in rotary lift contribution between the large and small radomes is approximately equal both in sign and magnitude to the car rotary lift contribution. The difference in rotary sideforce for similar [illegible] of these radomes was approximately twice the rotary sideforce of the car and this does not appear logical at all. The difference in rotary pitching moment contribution of the two radomes is positive (opposite in sign to hull contribution) and larger than the generally accepted value of hull rotary moment contribution of approximately .20.

At this point, it is felt that a note of caution must be expressed as to the validity of the car and large radome effects on the rotary derivatives. The large magnitudes of the effects are seriously doubted by the author and especially, in the case of car effects, in view of the discrepancy between pitch and yaw data. Therefore, since much of the Reference 1 and 2 car and radome effect data is conflicting, [illegible] and possibly due to the errors associated with differences between small numbers it is believed best to [illegible] to regard the effects of the car and radome on the rotary derivatives as relatively small and negligible.

b. Relative Effect and Accuracy of Hull and Tail Contributions

Since there is no proven theoretical method of calculating the hull contribution, its effect on the rotary lift, sideforce, and moments must be obtained exclusively from experimental data. The experimental data is meager in scope and amount (especially for rotary lift or sideforce) and exhibits trends which are not well defined. Although it appears that the available data does not yield a very accurate appraisal of the exact hull contributions this fact is not too serious with respect to the total airship rotary lift, sideforce, and moments. In the range of fineness ratios for present day airships ([illegible] 4 to 5) the hull contribution to the total rotary lift or sideforce is in the order of 10%, so errors in the order of [illegible]% in the hull alone estimated rotary lift would only change the total rotary lift by approximately 3%.

The hull contribution to the total rotary moment is also in the order of 10% or less and even a 50% error or deviation in the hull contribution, which might be possible, would only change the total airship rotary moment by approximately 5%.

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Therefore, since the tail contribution is the predominant factor in the prediction of the rotary derivatives of an airship, it is very important to be able to ascertain its most probable value with the greatest accuracy possible. Based on the tail damping factors, d_1 and d_2, plotted in Figures 6 and 7 it appears that the average deviation of all the tail lift damping factors from the best estimate (faired line) of this factor is in the order of 10%. It is believed that this deviation might be reduced further by the re-evaluation of the hull-tail force interference factor (η_F) and the use of the correlating geometric parameter, $\frac{S_T \ell_{t_S}}{V}$, for all available tail contribution data instead of the hull fineness ratio.

The maximum variation (excluding the H-tail) in magnitude of the tail moment damping factors, d_2, in Figure 6 at the same tail geometric parameter $\left(\frac{S_T \ell_{t_S}^2}{V^{4/3}}\right)$ is around 25% with an approximate average deviation from the faired line in the order of 10 to 15%. This deviation also might be reduced by a re-evaluation of the η_M factor. In Figure 7 the variation in the tail moment damping factor is much more severe. The maximum variation, from the assumed best value of d_2 = [illegible], is slightly over 50% with an average deviation from this value of approximately 20 to 25%. As noted above this could probably be reduced somewhat by the use of $\frac{S_T \ell_{t_S}^2}{V^{4/3}}$ as the correlating parameter and by the re-evaluation of η_M. Also, the questionable value of some of the old oscillation technique data has previously been noted and partially allowed for in the stated d_2 value but it is possible that some of this data should be completely ignored as far as modern non-rigid airships are concerned.

In conclusion it appears that even within the magnitude of the present analysis the data and correlating factors presented in Figures 6 and 7 would allow the prediction of the rotary lift and sideforce for present non-rigid airships within ±10% or less but the prediction of the rotary moments might be more inaccurate with possible errors as high as 15 or 20%. The rotary moments, it is believed, would probably be overestimated in magnitude rather than underestimated.

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V. PREDICTION OF AIRSHIP ROTARY DERIVATIVES ($\alpha = \psi = \delta = q = r = o$)

Although the present analysis of airship rotary derivatives (based on currently available test data and reports) is not considered sufficiently complete to unequivocably state that they have been determined, it is felt that with the utilization of the data and comments presented in this report the state of the art has been advanced and the rotary lift, sideforce, and moments can be predicted with greater certainty than has previously been accomplished.

The following method is presented as the best means developed under the scope and magnitude of this contract, to predict the rotary lift, sideforce, pitching moment and yawing moment.

The three basic assumptions that must be conceded are:

(1) The hull and tail rotary contributions can be directly added after their individual contribution is determined.

(2) The rotary effects of control cars, radomes and other protuberances is negligible.

(3) The rotary lift and pitching moment derivatives of the hull are equal to the hull rotary sideforce and yawing moment derivatives, as are the tail contributions except for any differences in the total tail area involved.

The first step is to ascertain the contribution of the hull to the rotary derivatives. This is accomplished entirely on the basis of the available experimental data and their variation with the hull fineness ratio as given in Figure 5 of this report. The values of C_{L_q} and C_{m_q} for the hull or envelope are read from the faired curves at the appropriate hull fineness ratio. In this discussion it is understood that even though only the longitudinal (or pitching velocity) derivatives are stated the equality of the directional (or yawing velocity) derivatives implies their values are equal for the hull and for the tail as long as the total tail areas and tail moment arms in pitch and yaw remain the same (including dihedral effects).

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The prediction of the tail contribution to the rotary derivatives is based on the previously defined equation for the theoretical rotary effects plus the correlating damping factors given in Figure 7 as best estimates based on available data.

The following equations yield the rotary lift and moment contributions of the airship tail.

$$C_{L_q}\ \text{tail} = \left[\frac{(C_{L_\alpha})_t\, S_T\, \ell_{t_\delta}\, \eta_F}{VOL}\right] d_1$$

$$C_{m_q}\ \text{tail} = \left[\frac{(C_{L_\alpha})_t\, S_T\, \ell_{t_\delta}^2\, \eta_M}{(VOL)^{4/3}}\right] d_2$$

where:

$(C_{L_\alpha})_t$ = Isolated tail lift-slope based on theory and experiment (Figure 2)

S_T = Total tail area (including effect of dihedral and included-hull area)*, Ft^2

ℓ_{t_δ} = Tail arm, C.B. to flap hinge line, ft

η_F = Hull-tail force interference factor (Figure 3)

η_M = Hull-tail moment interference factor (Figure 4)

d_1 = Tail force damping factor (Figure 7)

d_2 = Tail moment damping factor (Figure 7)

*Note: The general equation normally would have a dihedral angle function ($\cos^2 \Gamma$) as an integral part of the equation, since most modern non-rigid airships have tail configurations other than the conventional cruciform arrangement (+). However, since the dihedral function is modified for an inverted Y-tail configuration it is more convenient to include the dihedral correction in the value S_T which also includes any variation in naked tail areas due to non-similarity of the 2, 3 or 4 tail surfaces involved, which might differ in pitch and yaw calculations.

Once the hull and tail contributions have been obtained the results are added as noted in assumption (1).

$$C_{L_q} \text{ total} = C_{L_q} \text{ hull} + C_{L_q} \text{ tail}$$

$$C_{m_q} \text{ total} = C_{m_q} \text{ hull} + C_{m_q} \text{ tail}$$

It is appropriate at this time to evaluate the results of this method compared to the results obtained previously for a recent non-rigid airship. The comparison will be performed for the ZPG-3W airship whose rotary derivatives were estimated by other means and presented in Reference 22.

A. PREDICTED LIFT DUE TO PITCHING VELOCITY (ROTARY LIFT DERIVATIVE)

1. Envelope or Hull

a. Reference 22 Prediction

The rotary hull lift for the ZPG-3W airship is given in Reference 22 as being negligible or allowed for elsewhere.

$$C_{L_q} \text{ hull} \underset{\text{Ref. 22}}{=} 0$$

b. Present Analysis

From Figure 5 at a fineness ratio (L/D) of 4.70 we obtain:

$$C_{L_q} \text{ hull} = .17/\text{rad}$$

2. Tail Contribution

a. Reference 22 Prediction

The tail contribution to the rotary lift derivative is determined in reference [illegible] from the following equation:

$$C_{L_q}\ \text{tail Ref. 22} = \frac{C_{L_{\alpha\,t}}\, S_T\ l_{t_\delta}}{V(\ )^{2/3}} = \left(\frac{V}{V^{1/3}}\right)$$

where:

$(C_{L_\alpha})_t$ = 2.25 at Aspect Ratio = 1.67

S_T = 4330 Ft^2 (including dihedral effects and hull)

l_{t_δ} = 179.5 Ft

Vol = 1,465,000 Ft^3

$$C_{L_q}\ \text{tail}_{\text{Ref. 22}} = \frac{2.25\ (4330)\ (179.5)}{1,465,000} = 1.193/\text{rad}$$

b. __Present Analysis__

$$C_{L_q}\ \text{tail} = \left.\frac{C_{L_{\alpha\,t}}\ S_T\ l_{t_\delta}\ \eta_p}{VOL}\right]\ d_1$$

Where all values except η_p and d_1 are given previously and are obtained from Figures 3 and 7 respectively of this report and have approximate values of:

η_p = .50 at S_1/S_T = .40

d_1 = 1.30 at L/D = 4.70

$$C_{L_q}\ \text{tail} = \frac{2.25\ (4330)\ (179.5)\ (.50)}{1,465,000} \times 1.30$$

$$= .596 \,\Big]\, \times 1.30$$

$$C_{L_q}\ \text{tail} = .775/\text{rad}$$

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3. Total Rotary Lift.

Reference 22 gives $(C_{L_q})_{total} = 1.193/\text{rad}$

The present analysis gives $(C_{L_q})_{total} = (C_{L_q})_{hull} + (C_{L_q})_{tail}$

$$(C_{L_q})_{total} = .17 + .775 = .945/\text{rad}$$

The Reference 22 total rotary lift derivative is approximately 15 percent higher than that obtained by the method and values given in this report. However, there are some details which require clarification. One of these is the use and value of η_F. The author contends that it is improper and wrong to estimate rotary effects based on the isolated tail lift-slope without including the hull-tail interference factor (η_F). This factor is utilized in Reference 22 for the static tail lift derivative equation. This then, brings up the question of the correct value to be used since Reference 22 gives $\eta_F = .67$ and Figure 3 gives $\eta_F = .50$. The Reference 22 value for η_F is derived from Reference 21 data and has not been verified or correlated with other modern airship data. As an example of possible differences the values of η_F in pitch and yaw for an X-tail were determined from Reference 1 and 2 data to be approximately 0.58 and 0.68, respectively. The two values of η_F (.67 and .58) were determined from model tests conducted on practically identical full-scale configurations of an X-tail configuration in pitch. If values of $\eta_F = .67$ and .58 were used in the present analysis of the tail contribution to the rotary lift they would yield $(C_{L_q})_{tail}$ values of 1.038/rad and 0.90/rad, respectively. These are not completely valid though because changing the value of η_F would probably (if done for all available data) lower the value of the tail force damping factor (d_1). It appears that the net effect of changes in η_F and d_1 might be small, although this is not completely substantiated, and the present analysis in the case considered (ZPG-3W Airship) would still result in a total rotary lift derivative lower than previously estimated in Reference 22.

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B. PREDICTED PITCHING MOMENT DUE TO PITCHING VELOCITY (Rotary Moment Derivative)

1. Envelope or Hull

a. Reference 22 Prediction

$$C_{m_q} \text{ hull } _{\text{Ref. 22}} = -\frac{21.6}{V} \times \frac{V}{\forall^{1/3}} = -.19/\text{rad}$$

b. Present Analysis

From Figure 5 at L/D = 4.70 we obtain:

$$C_{m_q} \text{ hull } = -.20/\text{rad}$$

2. Tail Contribution

a. Reference 22 Prediction

$$C_{m_q} \text{ tail } _{\text{Ref.22}} = -\frac{C_{L_{\alpha t}} \, S_T \, t_\delta^2}{V \text{ (VOL)}} \times \frac{V}{\forall^{1/3}}$$

$$C_{m_q} \text{ tail } _{\text{Ref.22}} = -\frac{2.25 \, (4330) \, (179.5)^2}{1{,}465{,}000 \, (113.6)} = 1.888/\text{rad}$$

b. Present Analysis

$$C_{m_q} \text{ tail } = \frac{C_{L_{\alpha t}} \, S_T \, t_\delta^2 \, \eta_M}{V^{4/3}} \quad d_2$$

η_M = .40 (From Figure 4)

d_2 = 1.60 (From Figure 7 or this text)

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$$C_{m_q}\ \text{tail} = -\ \frac{2.25\ (4330)\ (179.5)^2\ (.40)}{16?,424,000} \times 1.60$$

$$= -\ .755 \times 1.60$$

$$(C_{m_q})\ \text{tail} = -\ 1.208/\text{rad}$$

3. Total Rotary Moment

$$(C_{m_q})_{\text{total}} = (C_{m_q})\ \text{hull} + (C_{m_q})\ \text{tail}$$

Reference 22 gives: $(C_{m_q})_{\text{total}} = -.19 + (-1.888) = -2.078/\text{rad}$

Present Analysis Gives: $(C_{m_q})_{\text{total}} = -.20 + (-1.208) = -1.408/\text{rad}$

The total rotary pitching moment derivative predicted by Reference 22 is almost 50% higher than that obtained by the present analysis. The same arguments concerning η_z for the lift, apply to the moment factor (η_M) used herein. Reference 22 gives η_M = .54 as derived from Reference 21 data while Reference 1 and 2 data yield η_M values of approximately .51 in pitch and .40 in yaw. As noted before the value of d_2 is directly dependent on the value of η_M but the reader is asked to recall that in the evaluation of d_2 from data of Reference 1 and 2 there appeared to be much smaller values of d_2 compared with other available data. Therefore, based on the latest modern non-rigid airship data the value of d_2 = 1.60 might be too high without any change in η_M. Based on all considerations involved it is readily apparent that the present analysis, or any additional revisions to it, would probably predict rotary moment derivatives that are significantly lower than those determined by the method utilized in Reference 22.

VI VARIATION OF ROTARY DERIVATIVES WITH ATTACK ANGLE, ANGULAR VELOCITY, AND FLAP DEFLECTION

In any study involving the analysis of the airships motion other than that in straight pitched flight or under the effects of small disturbances it is necessary to know the effect of angles of attack, flap deflection, and angular velocities greater or less than those near zero.

Experimental data obtained by the oscillation technique is generally considered inadequate for attack angles other than zero and since most of these data did not even measure the rotary moment derivative at angles of attack these data are ignored. Although the curved model tests conducted in the past included tests over a fairly wide attack angle and flap deflection range they were mostly conducted on rigid airship models, which have somewhat different aerodynamic characteristics compared to modern non-rigid airships, and were usually built to curvatures which represented quite moderate curvilinear motion or turning circles. In addition, there still exists some doubt as to the validity of the application of these data to curvatures, or angular velocities very much different than those to which the particular model was constructed.

Therefore, it appears that it would be necessary to depend on rotary data obtained by whirling arm tests to evaluate the effect of angle of attacks, flap deflections and angular velocities other than zero. The only tests conducted with variable angular velocity (i.e. turning radii) are those reported in References 1 and 2. Since considerable effort was expended in the basic correlation and determination of the rotary derivatives at or near zero attack angle and angular velocity it will not be possible to present a detailed analysis of these data within the magnitude of this contract. However, a few general comments are in order since these are essentially the only data by which the variation of the rotary derivatives with angle of attack flap deflection and angular velocity can be determined.

It is not possible at this time to separate the tail alone contributions so the following comments apply to the complete configurations tested, Hull + Car + Tail. The angular velocities in Reference 1 and 2 are expressed in the non-dimensional form of; $q' = \frac{q\ell}{V}$ with

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a range of values tested from $q' = \pm .078$ to $\pm .400$ which correspond to a range of R/L from 12.82 to 2.50, respectively. Generally the rotary lift derivatives appear fairly linear (for each individual model configuration) with respect to attack angles up to at least $\pm 5°$, dimensionless angular velocities up to $q' = \pm .200$ (R/L = 5.0) and flap deflections up to about $\pm 20°$. The rotary pitching moment derivatives are only linear for angles of attack of $\pm 2°$, dimensionless angular velocities only up to $q' = .1$, and flap deflections up to ± 10 or $\pm 15°$. Of course the range of linearity varies a little with each configuration and the H-tail configuration is practically linear throughout the α and q' range investigated. Beyond the linear ranges the derivatives or slopes vary significantly with the greatest changes occuring at the highest α and q' values. Reference 2 data also indicates approximately the same range of linearity for the yaw rotary derivatives with a slight tendency for an extension of the range with respect to angle of attack.

Therefore since a modern airship will usually have a minimum R/L = 2.0 ($q' = .500$) it appears that a large portion of airship motion analyses would be conducted in the non-linear range of the rotary derivatives. Thus a further extension or analysis of the Reference 1 and 2 data is desirable but not within the scope of this report. It is the authors opinion that the Reference 1 and 2 data can be utilized with reasonable confidence to obtain the rotary derivatives beyond their linear range (small disturbances) and are the only satisfactory data available at this time.

VII CONCLUSIONS AND RECOMMENDATIONS

Of the four experimental methods utilized to obtain airship rotary derivatives, the whirling arm technique and the method of curved or bowed models appear to offer the best results. The meager amount of data obtained with these methods along with some of the aerodynamic oscillator data forms the basis for the combined theoretical-empirical method developed to predict the rotary derivatives of airships.

It is assumed in developing the rotary derivative methodology that the hull and tail contributions can be added to each other and that the rotary derivatives are equal in pitch and yaw as long as the geometric parameters remain approximately the same. The prediction of the hull contribution is determined strictly from experimental

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data while the tail contribution is determined from an analysis and derivation of correlating factors based on experimental data and an equation which combines these factors with the theoretical approach.

The method developed to predict the airship rotary lift (or side-force) and pitching (or yawing) moment is believed to be more rigorous and justifiable than those utilized previously and in some cases would (particularly rotary moments) indicate significant differences in the predicted values. The reader is referred to Section V of this report for the method developed to predict rotary effects.

It is the authors opinion, expressed throughout this report, that it was not possible to establish a completely rigorous, reliable and defensible method to predict airship rotary derivatives within the scope and magnitude of this contract. There are three basic needs to enable one to thoroughly and accurately define airship rotary effects and they are as follows:

(1) A complete re-evaluation of the tail contribution of all past airship static and rotary derivative data with particular emphasis upon the correlating geometric parameters proposed in this analysis rather than the use of hull-fineness ratio as a correlating parameter for the tail contribution. This includes the re-evaluation and correlation of η_F and η_M.

(2) An analysis of the curved or bowed model technique of using one curved model to experimentally determine the effect of varying angular velocity and attack angle on the rotary derivatives as they might be used in any type of future motion analysis. Tests of models with varying curvature might be necessary to prove this hypothesis.

(3) A well defined, systematic, experimental determination of the rotary effects of airship hulls, tails, cars and other protuberances by either the whirling arm technique or the method of bowed models, whichever appears to be the most suited for the task.

The reasons and explanations as to why the first two items are required have been given in this report. The third item is necessary to define the variation of rotary effects for the complete range of the geometric and aerodynamic parameters which determine the rotary derivatives. Past damping derivative experiments have generally

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been performed on specific airships (mostly rigid) with very little systematic variation of the pertinent variables. The Reference 1 and 2 tests are an excellent beginning of this aim but suffered since the tests were conducted on only one hull (one L/D with tail surfaces designed expressly for that particular airship hull volume and L/D. The test envisaged by the author is by no means a simple task. Briefly, a rough outline of the type of testing required is given below.

(a) Test and measurement of the rotary effects of at least 10 bare hulls with fineness ratios varying from L/D = 2 to L/D = 12 all tested for a full range of angular velocities and attack angles.

(b) Test and measurement of these hulls with tail surfaces designed by present methods to yield adequate stability and control. These tests would also cover the full range of angular velocities and attack angles.

(c) Test and measurement of selected hulls with the same tail surfaces as above deliberately relocated closer or further from the C.G. to determine the effect of tail length, ℓ_{t_δ}, on the rotary derivatives and/or tests with the tail sizes (areas) varied to evaluate the effect of tail size alone on the rotary derivatives.

Item (a) will yield the effect of hull fineness ratio on the rotary derivatives for which insufficient reliable data now exists. Items (b) and (c) will yield the effect of the correlating parameters,

$$\frac{S_T \ \ell_{t_\delta}}{\mathcal{V}} \quad \text{and} \quad \frac{S_T \ \ell_{t_\delta}^{\,2}}{\mathcal{V}^{4/3}},$$ on the tail contribution to the

rotary derivatives and along with other available modern data would give an evaluation of the hull-tail interference factors (η_F and η_M) which is necessary to correctly predict rotary effects for present airships with modern tail surfaces.

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The purpose of the recommendations outlined herein is to resolve discrepancies in existing data and to provide a more accurate determination of the rotary effects on an airship or similar body. The method evolved in this report is an improvement but leaves much to be desired for a more accurate appraisal of the subject matter.

The determination of a method to predict or define airship rotary derivatives is Phase I of the contractors proposal to "Conduct Analysis and Model Tests to Improve the Predictability of Airship Flying Characteristics", and the contractor was granted the present contract for this Phase. Phase II consists of the experimental determination of the additional mass and moment of inertia. Phase III would utilize the information obtained in the previous phases, in conjunction with static aerodynamic characteristics, to compare the motion of an airship as obtained from analog computer solutions of equations of motion with the motion of an airship as measured during flight tests.

If it is agreed that the method presented in this report for predicting the rotary derivatives for small disturbances or motions is adequate without further refinement, tests, or analyses and that the reference 1 and 2 rotary data for various angles of attack and angular velocities are sufficiently reliable and accurate, (The author has previously stated that they are believed to be the only reliable data which can be utilized), the contractor would then feel that he is prepared to enter Phase II tests and preparation for Phase III computer programming. It has been noted in this analysis that with additional effort or tests, better rotary derivative data might be obtained but it is also true that the rotary derivative data presented are sufficient to provide acceptable information for Phase III. Some additional analyses might be conducted during Phase III to improve the data but it might be pointed out that the computer values utilized can be readily changed during the analog computer operation in order to satisfy the computer equations developed and the motion of the simulated airship. This latter process is essentially a trial and error determination of parameters that satisfy the equations of motion and would result in data that could be used to correlate existing data. The computer trial and error techniques would essentially serve as a verification (or rebuttal) of the rotary derivatives predicted by the method outlined in this report or could indicate possible areas of discrepancies. Therefore it is believed that work should commence as soon as possible on Phase II and III of the contractors proposal

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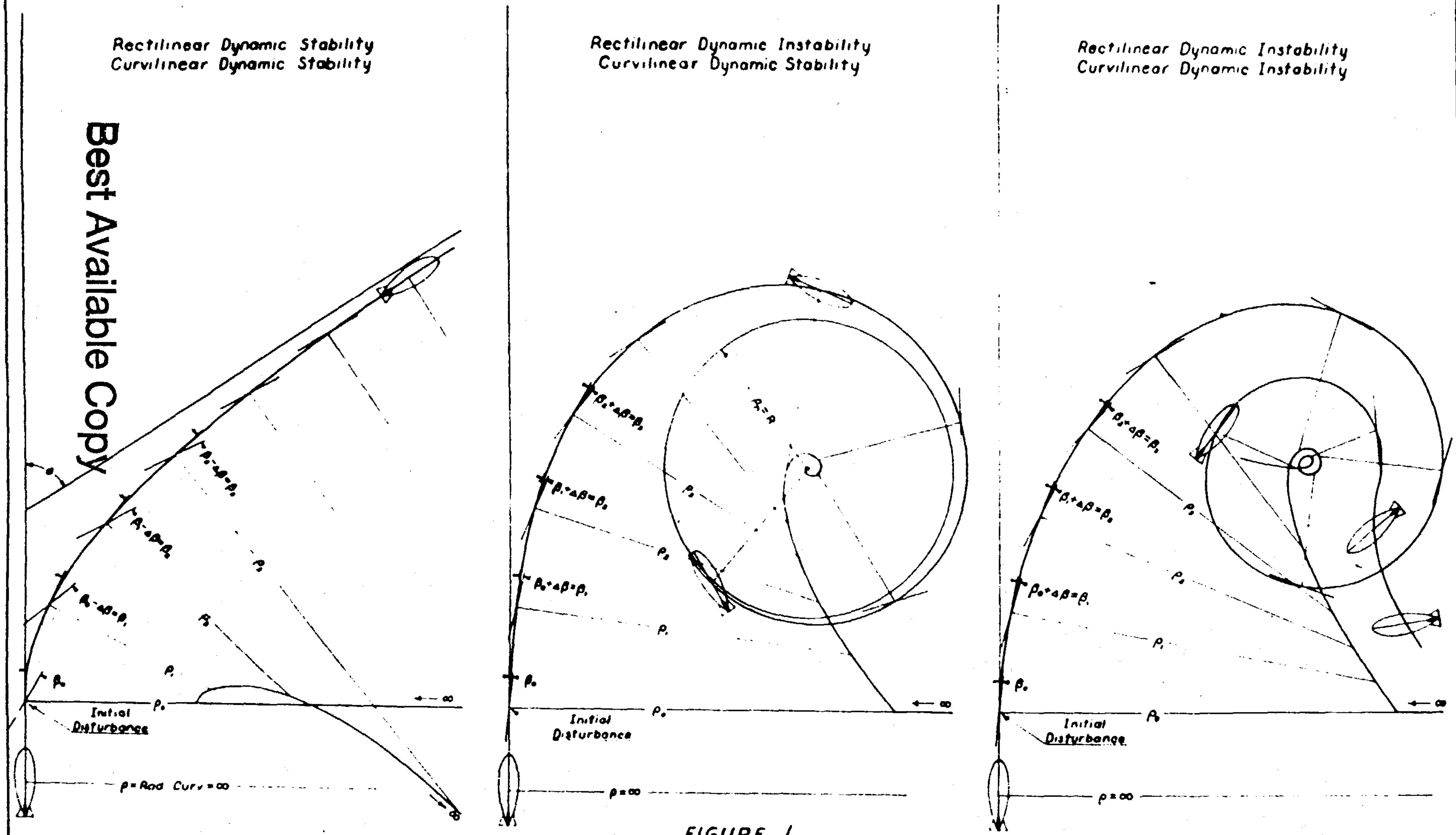


FIGURE 1

(a)
PATH OF AN AIRSHIP WHICH HAS RECTILINEAR AND CURVILINEAR DYNAMIC STABILITY UPON BEING DISTURBED

(b)
PATH OF AN AIRSHIP WHICH HAS RECTILINEAR DYNAMIC INSTABILITY BUT CURVILINEAR DYNAMIC STABILITY UPON BEING DISTURBED

(c)
PATH OF AN AIRSHIP WHICH HAS RECTILINEAR AND CURVILINEAR DYNAMIC INSTABILITY UPON BEING DISTURBED

FIGURE 2

EFFECT OF ASPECT RATIO ON THE LIFT SLOPE OF ISOLATED AIRFOILS

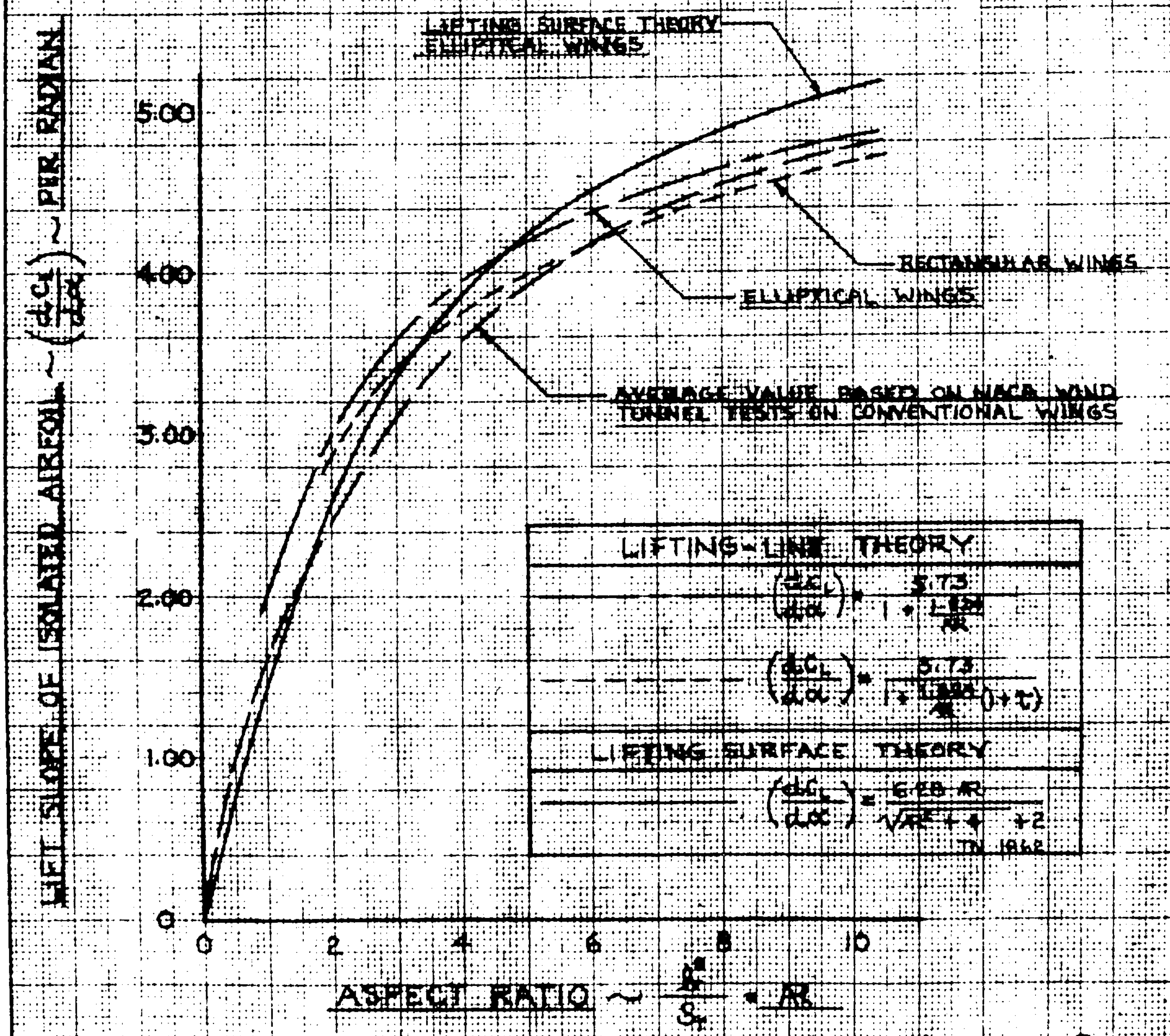
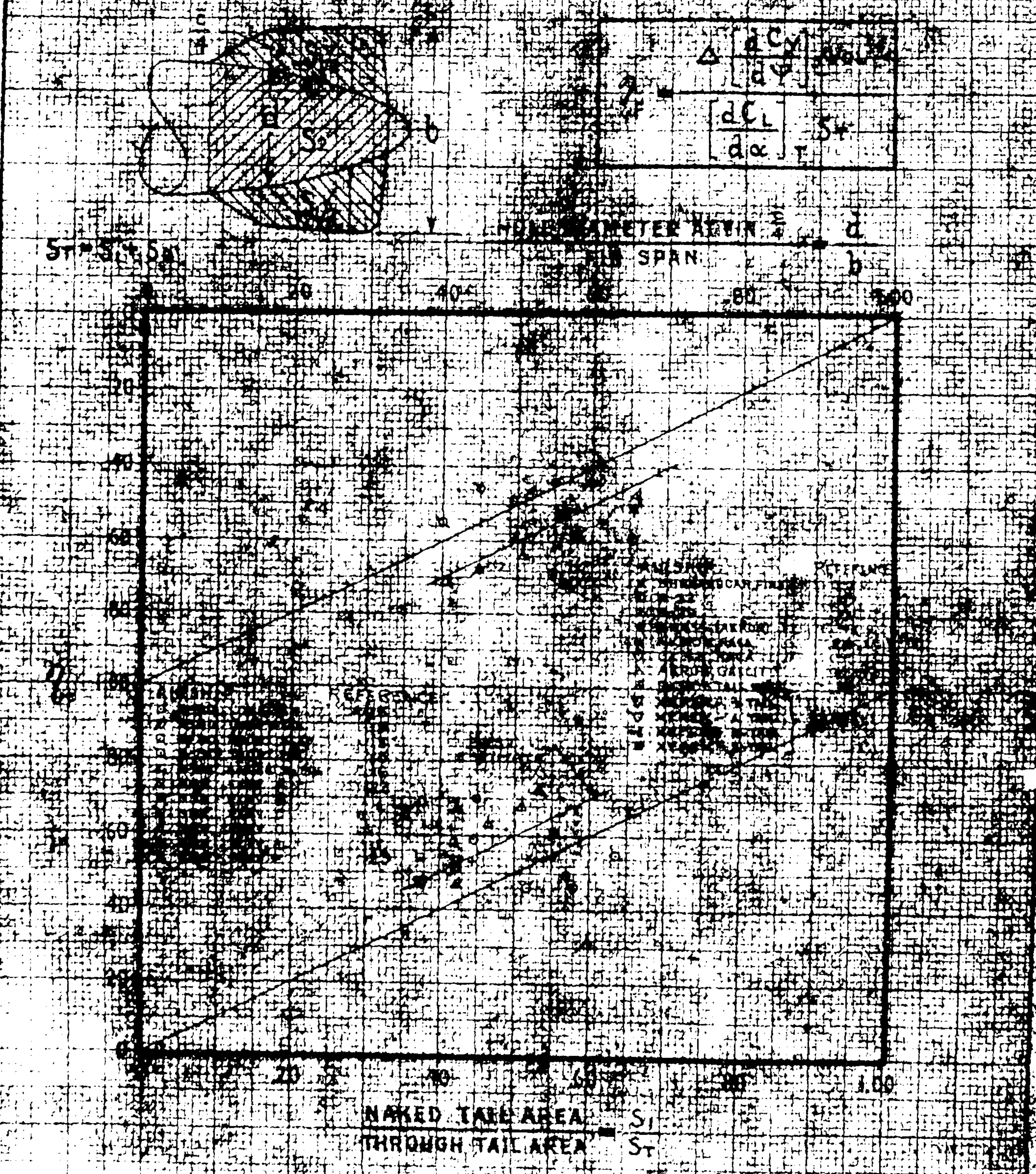


FIGURE 3

VARIATION OF THE HULL-TAIL FORCE INTERFERENCE FACTOR η_t WITH TAIL GEOMETRY FOR A GROUP OF REPRESENTATIVE AIRSHIP CONFIGURATIONS



$$\eta_t = \frac{\Delta \left[\frac{dC_Y}{d\psi}\right]}{\left[\frac{dC_L}{d\alpha}\right]_T S_T}$$

FIGURE 4

VARIATION OF THE HULL-TAIL MOMENT INTERFERENCE FACTOR η_M WITH TAIL GEOMETRY FOR A GROUP OF REPRESENTATIVE AIRSHIP CONFIGURATIONS

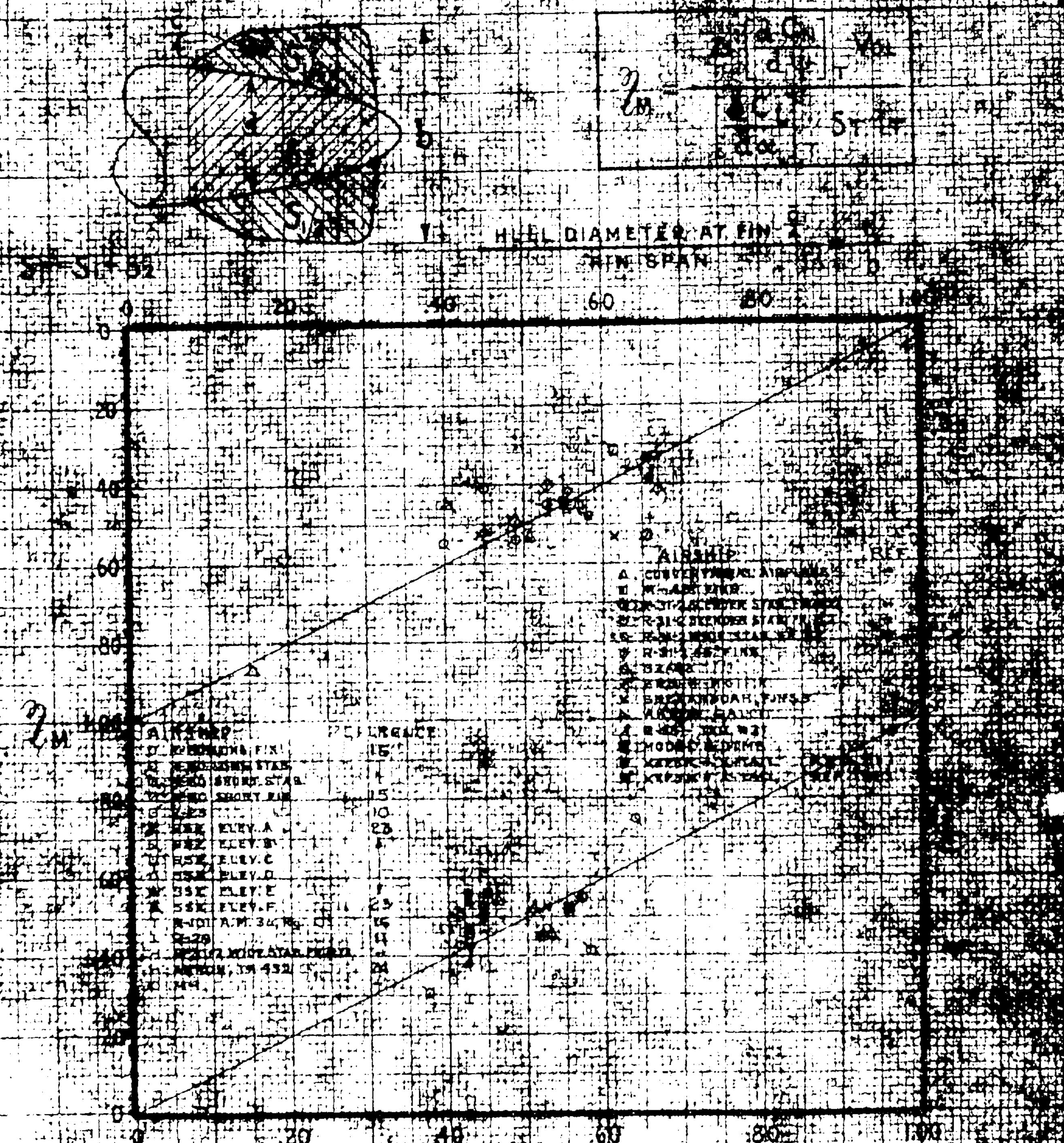


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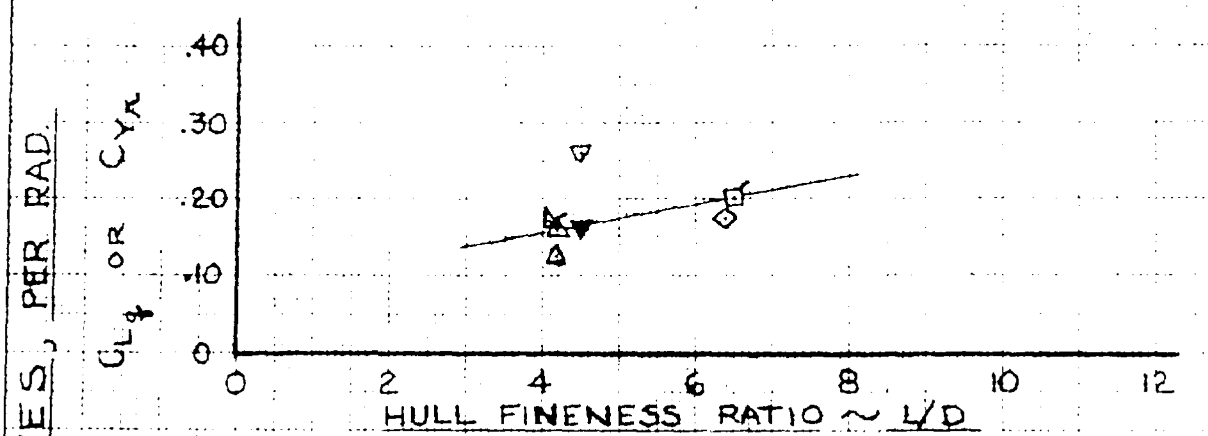
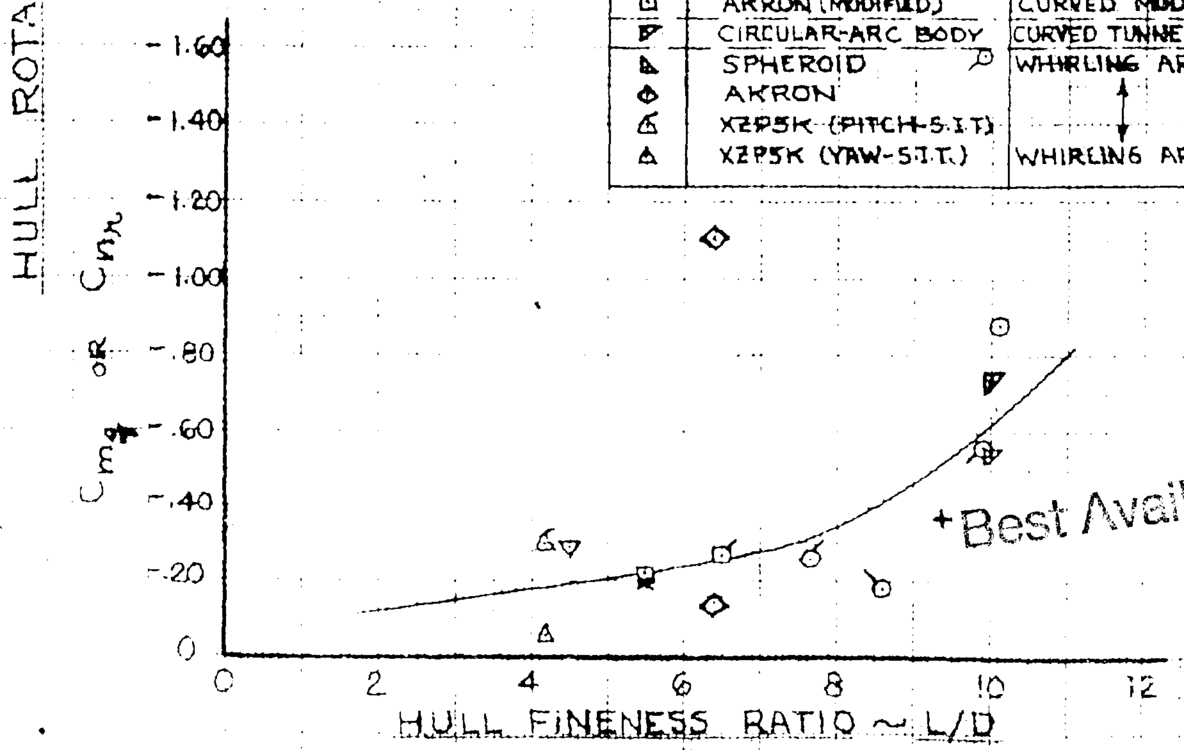
FIGURE 5

VARIATION OF AIRSHIP HULL ROTARY DERIVATIVES WITH HULL FINENESS RATIO BASED ON EXPERIMENTAL DATA



SYMBOL	AIRSHIP	TEST METHOD	REF
	R-23	AERO. OSCILLATOR	10
	R-29		11
+	R-32		12
	R-80		15
	R-101 (CIRCULAR)		16
x	R-101 (POLYGONAL)		16
	SHENANDOAH	AERO. OSCILLATOR	17
	V-2 NON-RIGID	CURVED MODEL	6
	AKRON (MODIFIED)	CURVED MODEL	8
	CIRCULAR-ARC BODY	CURVED TUNNEL	20
	SPHEROID	WHIRLING ARM	18
	AKRON		19
	XZP5K (PITCH-S.I.T.)		1
	XZP5K (YAW-S.I.T.)	WHIRLING ARM	2



PREPARED BY
CHECKED BY
DATE Nov. 15, 1960
REVISED

GOODYEAR
GOODYEAR AIRCRAFT CORPORATION
AKRON, OHIO

MODEL —
GER 10061
REF. NO.

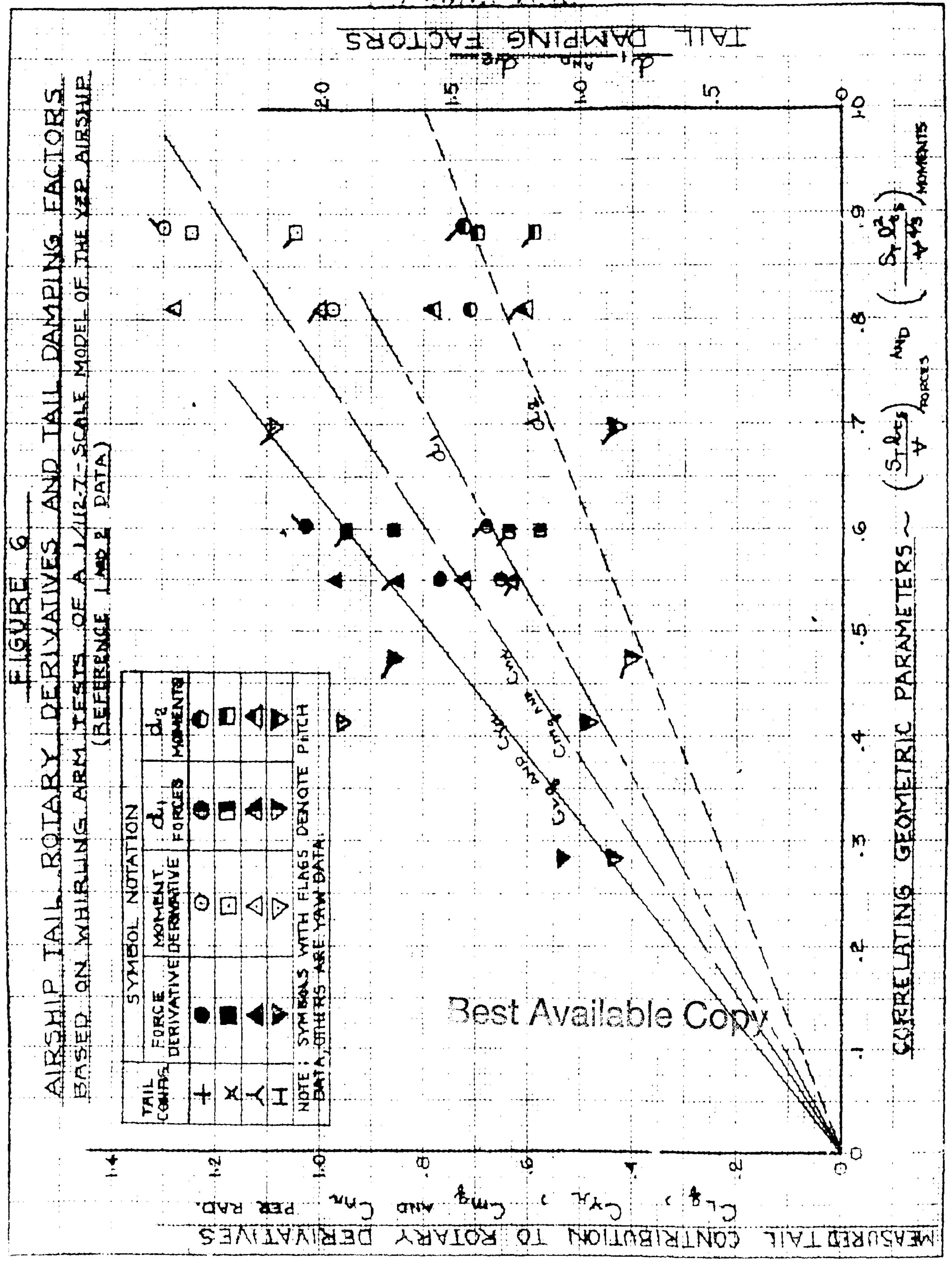


FIGURE 6
AIRSHIP TAIL ROTARY DERIVATIVES AND TAIL DAMPING FACTORS
BASED ON WHIRLING ARM TESTS OF A 1/112.7-SCALE MODEL OF THE YZ2P AIRSHIP
(REFERENCE 1 AND 2 DATA)

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FIGURE 7

DAMPING CHARACTERISTICS OF AIRSHIP TAIL SURFACES AS DETERMINED BY VARIOUS EXPERIMENTAL TECHNIQUES

(INCLUDING HULL-TAIL INTERFERENCE EFFECTS)